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Late Pleistocene-Holocene Marine Geology of Nares Strait Region: Palaeoceanography from Foraminifera and Dinoflagellate Cysts, Sedimentology and Stable Isotopes

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Abstract: A sediment-sampling program was carried out in the Nares Strait region during the Nares 2001 Expedition to obtain cores for high-resolution palaeoceanographic studies of late Pleistocene-Holocene climate change. Long cores (>4 m) were obtained from basins near Coburg Island, Jones Sound (Core 6, 75°35' N, 78°41'W), John Richardson Fiord off Kane Basin (Core 39, 80°09.6' N, 70°50.3'W), and in northeastern Hall Basin (Core 79, 81°28.3' N, 62°16.4' W). Short cores and grab samples were taken on shelves east and west of northern Smith Sound and in Kennedy Channel. Detailed studies of sediment texture, stable isotopes, microfossils and palynomorphs were made on the longest cores from Jones Sound and Hall Basin at the southern and northern ends of the Nares Strait region.

Core 6 is from a water depth of 561 m off Devon Island where the sea-ice cover (SIC) is presently >5/10 for nine months per year. Sediment is a bioturbated organic-rich clayey mud, with an age of 6315 ±60 years BP near the base. The mud has a mean grain size ranging ~3-4.5 μm. Peaks of sand and granules appear at about 3.4 ka BP and increase upward, suggesting greater influx of ice-rafted detritus over the past 2000 years. Sedimentation rates of 16-19 cm/century allow for decadal-scale palaeoceanographic studies. Abundant foraminifers and common small bivalve shells are present. Benthic faunas are diverse, with common calcareous and agglutinated species, predominantly *Reophax arctica* and *Textularia torquata.* In contrast, planktonic foraminifera are sparse and have heavy δ^{18}O isotopic values (~3-5 ‰), indicating that this fauna lives in the very cold (-1.5 °C), saline (33.5) water below the pycnocline at ~125 m. Large-scale (~2 ‰) oscillations in δ^{18}O values occur at intervals of about 2000 years. Palynomorphs include abundant dinoflagellate cysts, prasinophytes and foraminiferal linings; pollen and spores are also common. Palaeoceanographic reconstructions from dinocyst assemblages show that from ~6.5 to 3.3 ka BP, there were large oscillations in summer sea surface temperature (SST) from 3 °C cooler than now to 6 °C warmer, and that variations in SIC ranged from two months more to four months less of heavy ice compared to now.

In Hall Basin, Core 79 is from a water depth of 550 m near the Petermann Glacier where SST is -1.4 °C but the thermocline is shallow and the bottom water below 200 m is warmer (-0.4 to 0 °C) than in Jones Sound. SIC is presently about 8/10 for eleven months per year. Core 79 consists of dominantly clayey calcareous mud, with an upper unit of brown silty mud and scattered sand and has an age of more than 8.4 ka BP at the base. This overlies ~4 m of brown and gray coarsely banded mud with some finely laminated intervals and an age of 14.07 ka BP at the top. Shear strength is low (<8-12 KN m^{-2}) and shows no compaction by grounded ice. Planktonic and benthic foraminafera occur throughout and their δ^{18}O records are consistently lighter (3-4 ‰) than in Core 6, reflecting the warmer water below 50 m. The δ^{18}O signals are also less variable, suggesting smaller climatic oscillations on the polar margin than in Jones Sound. The diverse benthic assemblages are dominated by the calcareous species *Buliminella hensonii, Elphidium clavatum* and *Islandiella teretis.* The banded sediment has low numbers of benthic *foraminifera dominated by Cassidulina reniforme and* Elphidium clavatum, with relatively high percentages of *Buliminella hensoni, Islandiella teretis* and some *Stetsonia arctica* indicating Arctic Ocean slope to deep-water conditions. The banded sediment represents deposition under pack ice or a floating ice shelf and there is no evidence of grounded ice in eastern Hall Basin during at least the past 14 ka BP.

Zusammenfassung: Während der Nares-Expedition 2001 wurden die Sedimente im Gebiet der Nares Strait beprobt, um Kerne für hochauflösende paläozeanographische Untersuchungen des pleistozänen bis holozänen Klimawandels zu gewinnen. Kerne mit einer Länge von über 4 m wurden aus Sedimenten des Jones Sound bei Coburg Island (Kern 6: 75°35' N, 78°41' W), im John Richardson Fjord am Kane Basin (Kern 39: 80°09,6' N, 70°50,3' W) und im nordöstlichen Hall Basin (Kern 79: 81°18,3' N, 62°16,4' W) gewonnen. Kurze Kerne und Dredgen wurden auf den Schelfrändern östlich und westlich des Smith Sound und im Kennedy Channel genommen. An den langen Kernen vom Jones Sound und Hall Basin wurden Sediment-Textur, stabile Isotope, Mikrofossilien und Palynomorphe detailliert untersucht. Kern 6 stammt aus einer Wassertiefe von 561 m vor Devon Island, wo die Meereisbedeckung während neun Monaten im Jahr über 5/10 beträgt. Das Sediment ist ein bioturbater toniger Schlick reich an organischer Substanz, der nahe der Basis ein Alter von 6315 ±60 years BP ergab. Der Schlick hat eine mittlere Korngröße von 3-4,5 mm. Höhere Sand-Gehalte erscheinen bei ca. 3,4 ka BP und nehmen nach oben hin zu, was vermutlich auf eine Zunahme von Eis transportiertem Detritus während der letzten 2000 Jahre hinweist. Sedimentationsraten von 16-19 cm J-1 ermöglichen paläoozeanographische Auflösungen in der Größenordnung von Jahrzehnten. Foraminiferen und kleine Bivalven-Schalen sind häufig. Die benthischen Faunen sind artenreich mit häufigen kalkschaligen und agglutinierenden Arten, vor allem *Reophax arctica* und *Textularia torquata.* Im Gegensatz dazu sind planktische Foraminiferen selten und weisen hohe δ^{18}O-Werte auf (ca. 3-5 0/00), ein Hinweis auf den sehr kalten (-1,5 °C) und salzigen (33,5) Lebensraum unterhalb der Pyknokline bei 125 m Wassertiefe. Großmaßstäbige Änderungen der δ^{18}O-Werte (um 2 0/00) sind in Abständen von ca. 2000 Jahren zu beobachten. Die Palynomorphen umfassen Dinoflagellatenzysten, Prasinophyten und Foraminiferen; Pollen und Sporen sind ebenfalls häufig. Paläoozeanographische Rekonstruktionen mittels Dinozysten-Vergesellschaftungen belegen von 6,5 bis 3.3 ka BP größere Oszillationen der Sommertemperaturen an der Wasseroberfläche zwischen 3 °C kühler bis 6 °C wärmer als heute. Gleichzeitig dauerte die Eisbedeckung zwei Monate mehr bis vier Monate weniger als heute.

Kern 79 stammt aus einer Wassertiefe von 550 m im Hall-Becken nahe dem Petermann-Gletscher. Die SST beträgt hier –1,4 °C, aber die Thermokline ist flach und das Bodenwasser unter 200 m ist wärmer (-0,4 bis 0 °C) als im Jones Sound. Die heutige Meereisbedeckung liegt bei ca. 8-10 Zehntel während elf Monaten im Jahr. Kern 79 besteht überwiegend aus tonig-kalkigem Schlick mit einer oberen Einheit von braunem siltigen Ton mit gelegentlichem Sandgehalt und einem Alter von 8,4 ka BP an der Basis. Darunter folgen ca. 4 m braune und graue, grob-gebänderte Tone mit einigen feinlaminierten Intervallen. Das Alter am Top dieser Folge beträgt 14,07 ka BP. Die Scherfestigkeit ist gering (8-12 KN m^{-2}), es fehlen Hinweise auf Kompaktion durch Eis. Planktonische und benthonische Foraminiferen kommen im ganzen Kern vor. Ihre δ^{18}O-Werte sind generell geringer (3-4 0/00) als in Kern 6, ein Effekt des wärmeren Wassers unter 50 m. Die δ^{18}O-Werte sind außerdem weniger variabel, was als Hinweis auf geringere klimatische Oszillationen am Rande des polaren Ozeans hinweist als im Jones Sound. Die artenreichen benthischen Gemeinschaften werden von den kalkschaligen Arten *Bulminella hensonii, Elphidium clavatum* und *Islandiella teretis* dominiert. Das gebänderte Sediment enthält wenige benthische Foraminiferen, dominiert durch *Cassidulina reniforme* und *Elphidium clavatum* mit einem relativ hohen Anteil an *Buliminella hensonii, Islandiella teretis* und einigen *Stetsonia arctica,* die auf Lebensräume am Hang und im Tiefwasser des arktischen Ozeans hinweisen.Das gebänderte Sediment ist Ausdruck der Ablagerung unter Packeis oder einem schwimmenden Eisschelf. Es gibt keinerlei Hinweis auf aufliegendes Eis im östlichen Hall-Becken während der letzten 14 ka BP.

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INTRODUCTION

Nares Strait is a long (~500 km), narrow (~50-120 km) seaway between Ellesmere Island and Greenland that connects the Arctic waters of the Lincoln Sea (~82 °N) to the sub-arctic waters of the West Greenland Current in northern Baffin Bay (~76 °N). The deep basins (~400-600 m) of Smith Sound and Hall Basin occupy the southern and northern ends of Nares Strait (Fig. 1), but the central Kane Basin is relatively shallow (<300 m). The narrow, relatively shallow straits of Smith Strait and Kennedy Channel (average ~200 m) link the deep basins to the northern and southern ends of Kane Basin; the deeper Robeson Channel (~400 m) connects Hall Basin to the Lincoln Sea in the southern Arctic Ocean. Jones Sound and Coburg Polynya (located immediately south of Coburg Island) form the west side of the Nares Strait region, between Lancaster and Smith Sounds.

The history of sea ice and glacier ice in the Nares Strait region is thought to be a critical factor determining the long-term (millennial-scale) exchange of surface water between the Arctic Ocean and Labrador Sea during the late Quaternary period (Aksu & Piper 1979, Aksu 1983, England 1999). At present, about one Sverdrup of cold, low salinity (~32 psu) Arctic surface water flows through the Strait and sustains the cold Baffin (= Baffin Land) and Labrador currents of the Canadian Arctic islands and mainland. This volume is about 30 % of the present-day total outflow of surface water from the Arctic Ocean to the Atlantic Ocean (Agaard & Carmack 1989). Blockage of Nares Strait by grounded glacier ice, however, could significantly reduce the inflow of Arctic water to the northwest Atlantic and allow northward penetration of relatively warm West Greenland Current water into Baffin Bay during glacial intervals (Aksu & Piper 1979, Aksu & Mudie 1986).

Marine sediment cores from deep water sites provide continuous records of microfossil and sediment deposition in contrast to the discontinuous records of mollusks, foraminifers and driftwood found on raised beaches of the Nares Strait region (e.g., England et al. 2000, Bennike & Björck 2002). Quaternary microfossil and palynological records from the northern Labrador Sea (Scott et al. 1989a, Aksu et al. 1989, 1992) and the central Arctic Ocean (Mudie 1985, Aksu et al., 1988, Scott et al. 1989b) show multi-millennial scale oscillations in sea surface temperature (SST) of 4-8 °C that correspond to glacial-interglacial cycles in the Labrador Sea. Dinoflagellate cyst (dinocyst) records from Labrador Sea and southern Baffin Bay (de Vernal et al. 1994, de Vernal & Hillaire-Marcel 2000) also show glacial-interglacial changes in sea surface temperature (SST) and salinity of about 2-5 °C and 2-4 psu, respectively. Corresponding changes in the duration of >50 % sea-ice cover (SIC) range from one to six months. These large-scale changes in SST seem to support the idea of restricted Arctic Water inflow during the later parts of each glacial cycle. The paucity of marine mollusks older than 10.1 ka BP from northern and central Nares Strait (England 1999, England et al. 2000, Bennike & Björck 2002) and Northwest Greenland (Bennike 2002), together with Cl-36 ages from Hans Island in Kennedy Channel (Zreda et al. 1999), further suggest that continental ice filled part of Nares Strait until about 10 ka. Apparently very large uplift rates in northern Greenland may also reflect ice loading in Nares Strait (Bennike 2002) but the ages and elevations of the marine limits are presently poorly constrained (Bennike 2002) and faulting on the Polar Margin may also have contributed to the apparently high rate of uplift (Hein & Mudie 1991). Glacio-morphological and mollusk data (Dyke 2000) also indicate an extensive Late Wisconsinan Innuitian Ice sheet and a late (~10 ka) retreat of the Devon Icecap. However, the only previous high-resolution paleoceanographic study with radiocarbon age control (Levac et al. 2001) does not indicate grounded ice in Smith Sound at 10.4 ka BP (uncorrected age ~10 ka BP). Thus, important questions remain regarding the extent of the Ellesmere and Greenland ice sheets across Nares Strait at the end of the last glaciation, and the timing of ice retreat from Nares Strait.

Other interest in the paleoceanographic history of the Canadian Arctic Archipelago (CAA) is focused on the recent decrease in sea ice and the possibility that the Northwest Passage through Lancaster Sound to Beaufort Sea may become ice free in summer (e.g. Lange et al. 1999). Historical oceanographic measurements over the past ~50 years show that the annual temperature in the western Canadian Arctic has increased by ~0.6-1.2 °C (Overpeck et al. 1997) and there has been an 8 % reduction in sea ice extent since 1978 (Couture & Bancroft 2003). These historical values are presently used to initialize and constrain global circulation models (GCMs) to predict future climate change in the Canadian Arctic. The results suggest that by 2070, there will be a 2-4 °C increase of SST between Baffin Bay and the Central Arctic Ocean (MacKenzie 2003). The historical records, however, are too short to allow realistic evaluation of the GCM estimates. The palynological records from North Water Polynya (NOW) and Coburg Polynya show quasi-cyclical changes of 2-4 °C at intervals of about 1000-1500 years for the past 8000 years (Levac et al. 2001, Mudie et al. in press), and archaeological evidence shows major century-scale changes in hunting modes of paleo-Eskimo peoples that may reflect climate changes during the past 4000 years (e.g. Savelle & Dyke 2002; Mudie et al. 2005). The century-scale resolution of these paleoclimatic temperature estimates, however, is presently too low to be used for the GCM models.

During Cruise 2001 of the CCGC "Louis S. St. Laurent", long sediment cores were recovered from offshore basins with a thick cover of Pleistocene-Holocene mud to further examine the question of late glacial ice extent in Nares Strait, and to obtain decadal-scale records of Holocene changes in sea surface temperature (SST), salinity and sea ice cover (SIC). We report here the initial results of sedimentological, geochemical, micro-paleontological and palynological studies of cores from the southern and northern ends of Nares Strait that provide new evidence regarding the extent of grounded ice in Nares Strait at 10 ka BP and the magnitude of the decadal-scale changes in SST, salinity and SIC.

METHODS

Fieldwork

Huntec high-resolution seismic survey methods were used to locate areas with thick Holocene sediment cover (Fig. 2a, 2b) and within these areas, core sites were selected using 12 kHz

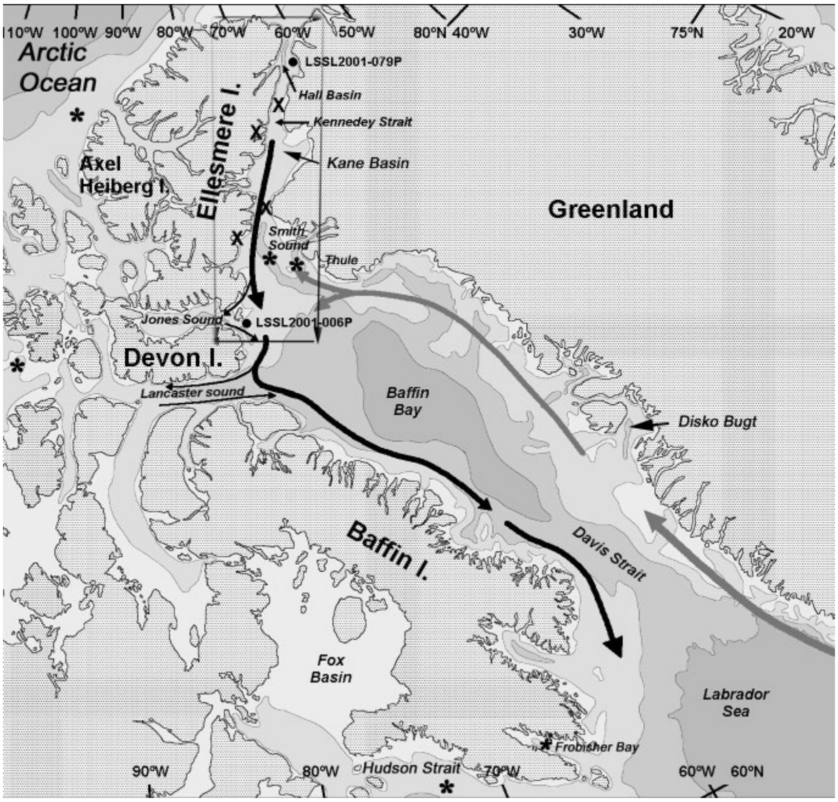

Fig. 1a: Map of eastern Canadian Arctic and western Greenland, showing the positions of Nares Strait, Disko Bugt, Frobisher Bay, and sites of previous studies (*), locations of LSSL2001 long cores (•) and other samples (x) from Cruise LSSL2001, and arrows showing surface currents (bold black = Arctic Surface Water; gray = mixed Arctic and North Atlantic Water). The rectangle delineates the Nares Strait study area.

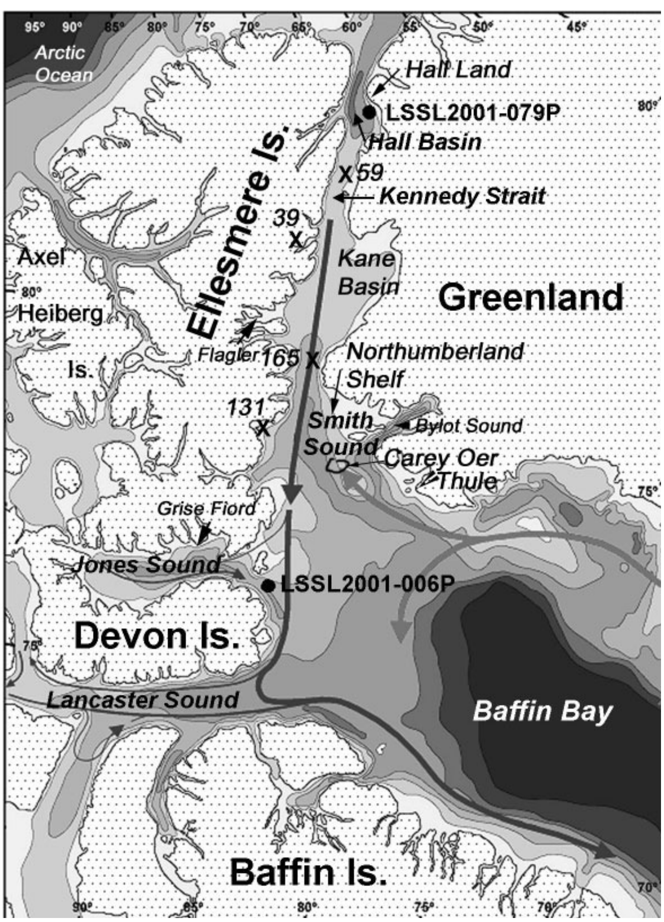

Fig. 1b: Map of Nares Strait and northeast Canadian Arctic showing locations of cores and other study areas and place names mentioned in the text. Detailed bathymetry = 100, 200, 500 and 1000 m contours; core locations = bold dots; other samples = x; arrows showing surface currents as in Fig. 1a.

echograms (see Jackson et al. 2002). A large box core or Van Veen grab was first taken to retrieve the surface layer (for details see Jackson et al. 2002). A Benthos piston corer with 30-50 m of barrel was then used to recover long cores from the forward deck of the ship. Benthos trigger weight (TWC) and piston cores were cut into ~1.5 m-long sections, capped, sealed in beeswax and stored upright in a refrigerated room at 4 °C. One to two days after recovery, the cores were split, photographed and visually described. Core descriptions included HCl tests for carbonate reactivity and visual examination of the >63 μm sediment fraction at intervals of about 50 cm. The piston cores were sampled for bulk density at about 1 m intervals immediately after splitting the cores. Core penetrometer measurements were made on the archive halves of the split TWC and piston cores. The cores were sampled at 10 cm intervals for palynology (20 cm^3) at 5-10 cm intervals for foraminifera, oxygen isotopes and grain size analysis (40 cm^3). Mollusk shells were also removed from Core 6 for radiocarbon analysis at the AMS laboratory at Utrecht University, The Netherlands.

Laboratory analysis

X-radiographs, shear strength and magnetic susceptibility measurements were made on the archive core halves in the GSCA Core repository at Bedford Institute of Oceanography, Dartmouth, Nova Scotia.

A Fritsch A22 laser particle-sizer was used to analyse the grain-size distribution of the detrital (siliciclastic) sediment fraction (0.15-1682 μm). Organic carbon, carbonate and biogenic opal were removed prior to the grain-size analysis by treatment with excess H_2O_2, HCl and NaOH, respectively. Details on the methods and laser particle-sizer used are given

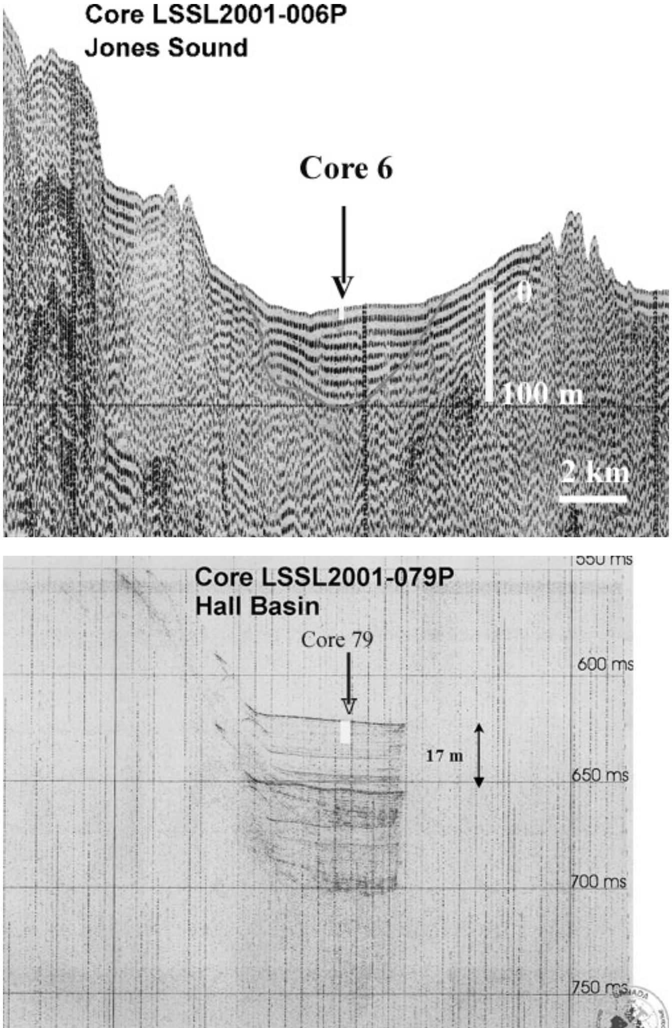

Fig. 2: Seismic profiles of core sites. (top) = Core LSSL2001-006P, deep-water area of Coburg Basin south of Coburg Island; air-gun data of MacLean et al. (1984). (bottom) = Core LSSL2001-079P, Hall Basin from Huntec data of Jackson et al. (2002).

in Konert & Vandenberghe (1997).

Stable oxygen isotopes ($\delta^{18}O$) were measured on planktonic and benthic foraminifera, using a Finnigan MAT 252 mass spectrometer combined with an automatic Finnigan MAT carbonate preparation line. For each analysis, two to six for aminifers were handpicked from the 125-250 μm size fraction (>250 μm for *Nonionella labradoricum*). The $\delta^{18}O$ reproducibility of a routinely analyzed carbonate standard (NBS 19) is better than 0.1 ‰ (1 σ). The isotope values are given with respect to the PDB standard.

For chronological control, AMS ^{14}C measurements were made on molluscs (Core 6) or on mixed planktonic-benthic foraminifers (Core 79). The foraminifera used for dating included only *Neoquadrina, Islandiella* and *Elphidium;* no miliolids were included. The planktonic and large calcareous forams hand-picked for radiocarbon dating are sand-sized particles and are not present in the shallow nearshore zone where forams may be redeposited by wave action or cryoturbation. The AMS measurements were made at the AMS ^{14}C dating facilities of University of Aarhus and Utrecht University, respectively. Radiocarbon ages are reported here (Tab. 1) as uncorrected values in order to make direct comparisons with the ages given in most other studies, and because there is still dispute over the value of the marine reservoir correction age (400 *versus* 440 or more years) in the Canadian Arctic. However, Table 1 also shows the calendar ages that were obtained by using the computer program Calib 4.2 (Stuiver & Reimer 1993) that assumes a 400 year marine reservoir age.

Samples of 20 cm^3 volume were wet-sieved through nested sieves of >45, >63, and >500 μm-sieves to retain foraminifera on the smaller sieves and to remove large clasts of the largest sieve. Samples were preserved in ethanol and examined with a dissecting microscope at magnifications of x20 and x40. Preservation was generally good for both calcareous and agglutinated species.

Palynomorphs were extracted from samples of 2-5 cm3 volume, using standard methods for Quaternary marine sediments (Rochon et al. 1999): sieving at 10 and 125 μm mesh sizes, digestion in HCl and HF, and adding exotic spores to obtain estimates of palynomorph concentration per cm. Quaternary palynomorph preservation is good in most sections of the cores, but all samples included common reworked pre-Quaternary (mainly Tertiary) triporate pollen and Mesozoic pollen and spores; reworked dinocysts are rarely present. The reworked palynomorphs were primarily recognized by their distinctive morphology and very dark color, but flattened and/or yellowish grains of extant pollen types were also scored as reworked.

One or two slides of each processed sample were counted at x25 magnification, until a minimum of 300 exotic spores was reached. This yielded counts of 100-200 for total dinocysts in the middle to upper Holocene samples; however, in the late glacial to early Holocene intervals, counts were as low as 25-50 for two slides and >1000 exotic spores. Nomenclature of the dinocysts follows that used by Williams et al. (1998) and Rochon et al. (1999) except where noted. During the counting

Lab. No.	Sample number	Depth (cm)	Material	$\partial^{13}C$	Total C (mg)	Uncorrected ^{14}C age BP	calendar age BP
Utc12040	LSSL2001-79PC	17	forams	0	0.25	2995 ±44	2803-2721
Utc12041	LSSL2001-79PC	83	forams	1.6	0.19	5017 ±47	5422-5312
Utc12042	LSSL2001-79PC	181	forams	-0.3	0.43	12910 ±70	15214-14713
Utc12043	LSSL2001-79PC	258	forams	-2	0.05	8480 ±110	9057-8819
Utc12044	LSSL2001-79PC	322	forams	-1.6	0.29	14070 ±100	16542-16048
AAR-505	LSSL2001-006PC	518	shell	-9.95		3405 ±55	1730-1690 BC
AAR-506	LSSL2001-006PC	530	shell	-0.88		3375 ±42	1684-1645 BC
AAR-507	LSSL2001-006PC	1080	shell	-1.62		6315 ±60	5355-5215 BC

Tab. 1: Radiocarbon ages of samples in this study. Ages are corrected for isotopic fractionation but not sea water age.

of dinocysts, pollen and fern + moss spores, records were kept of the number of microforaminiferal linings, acritarchs, and freshwater algae, including prasinophytes and coenobia of *Pediastrum* and *Botryococcus.*

Quantitative data derived from transfer functions

Decadal-scale quantitative records of changes in sea surface parameters (SST and SSS in summer and winter, and sea ice cover) have been obtained using dinocyst assemblages as proxies. Dinocyst assemblages from the tops of box-core samples at 677 Arctic sites (DE VERNAL et al. 2003) have been calibrated against the oceanographic data to develop paleoclimatic transfer functions using the biogeographical closest analogue method (ROCHON et al. 1999). For this study, log transformed data for 54 dinocyst species grouped into 40 taxa were used, and the reconstructed values are the weighted average of the ten best analogues.

RESULTS

Core 6, Coburg Polynya, Jones Sound, 561 m

Core LSSL2001-006 (Core 6) was recovered from a water depth of 561 m in the Coburg Polynya near the southern entrance to Jones Sound, at 75°35.19' N, 78°41.58' W. Here the summer SST is 2.5 - 4 °C and the surface salinity is ~31.8 (Fig. 3), and SIC is nine months per year. The core site is located downstream of melt-water discharged by several outlet glaciers draining the Devon and Ellesmere Island icecaps (TAYLOR & FROBEL 1984, HORNE 1989). Sea surface temperature and salinity rise rapidly from about 2 °C and 28 psu at the glacier front to 4 °C and 31.7 near the core site. The thermocline and halocline are at about 125 m depth where temperature drops to -1.5 °C and salinity increases to 33.5.

Core 6 was taken from the center of the Coburg Basin (shown by the 500 m contour in Fig. 1) and consists of 11 m of bioturbated organic-rich, gassy olive-gray mud, with a clayey interval from 9.5-8.5 m and a *Portlandia arctica* mollusk age of 6315 ±60 years BP at 10.8 m (Fig. 4A, 4B). Two other mollusk shell ages of 3775 ±42 and 3805 ±55 years BP at 5.3 and 5.18 m depth show that sedimentation rates range from about 19 cm/century from ~7-3.3 ka BP to a slightly slower rate of ~16 cm 10^{-2} years during the late Holocene. A neighbouring core (HU8-023-052) located about 10 km away on the edge of Coburg Basin in 1983 (MACLEAN et al. 1984; WILLIAMS 1990) and recovered about 5 m of gassy mud with a shell age of 6990 ±72 years BP at 4.9 m, below which was banded glaciomarine sediment, and gravelly till with shell fragments with an age of 30290 ±2490 years BP for the interval 8.75-8.9 m (Fig. 4C).

Shear strength values for Core 6 (Fig. 5) are less than 6 KN m^{-2}, except for the clayey interval from 9.5-8.5 m with anomalously high values for a section where the core liner cracked during extraction from the sediment. Magnetic susceptibility is also low throughout (<8 SI units), although there are broad peaks from ~11-10, 7.5-6.5 and 3-1 m that generally correspond to intervals of lighter $\delta^{18}O$ isotope values for the planktonic foraminifera. The clayey mud (75-85 % clay, <1 % sand) is fine-grained throughout, with mean grain size ranging from ~3 to 4.5 μm. Small peaks of sand and fine gravel begin at about 3.4 ka BP. Sand and fine gravel increase upwards in the trigger weight core that has an estimated age of about 125 ka at 15 cm, based on ^{210}Pb ages for other cores from

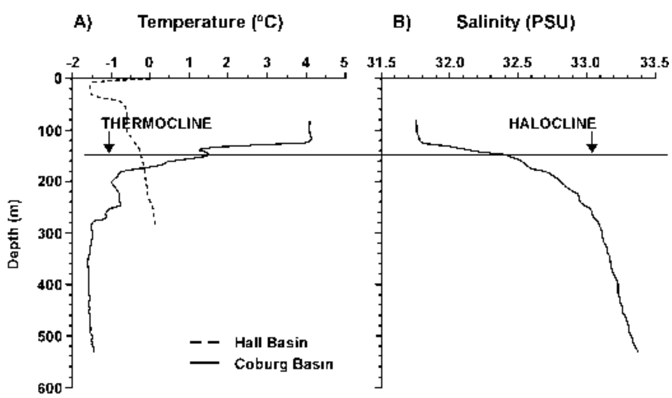

Fig. 3: CTD profiles taken near the core sites a few hours before coring. A) = Temperature near site LSSL2001-006 (solid line), 08 August 2001, and at Hall Basin site of Core LSSL2001-079, 02 September 2001 (broken line). B) = Salinity record near site LSSL2001-006. All data from P. Jones, Bedford Inst. of Oceanography, 2003.

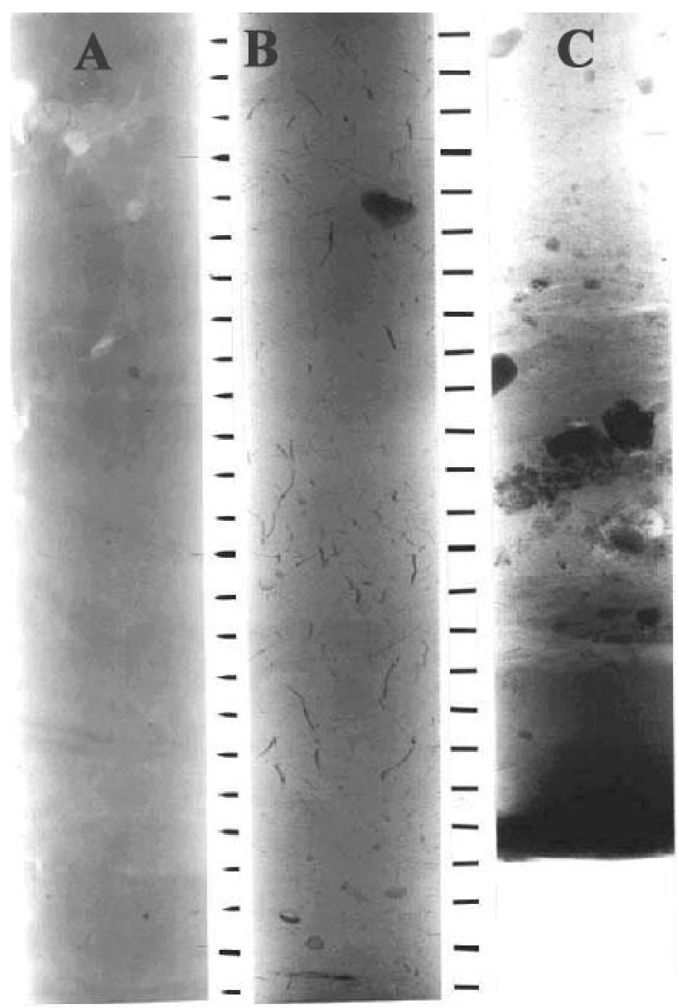

Fig. 4: X-radiographs of cores. A & B Coburg Polynya, Core LSSL2001-006; A = TWC 20-40 cm, showing very faint silt laminae and rare granules; B = BPC 520-540 cm, showing pyrite-infilled burrows and small, paired bivalves. C = Core HU83-023-052, base, showing gravelly, sandy diamicton.

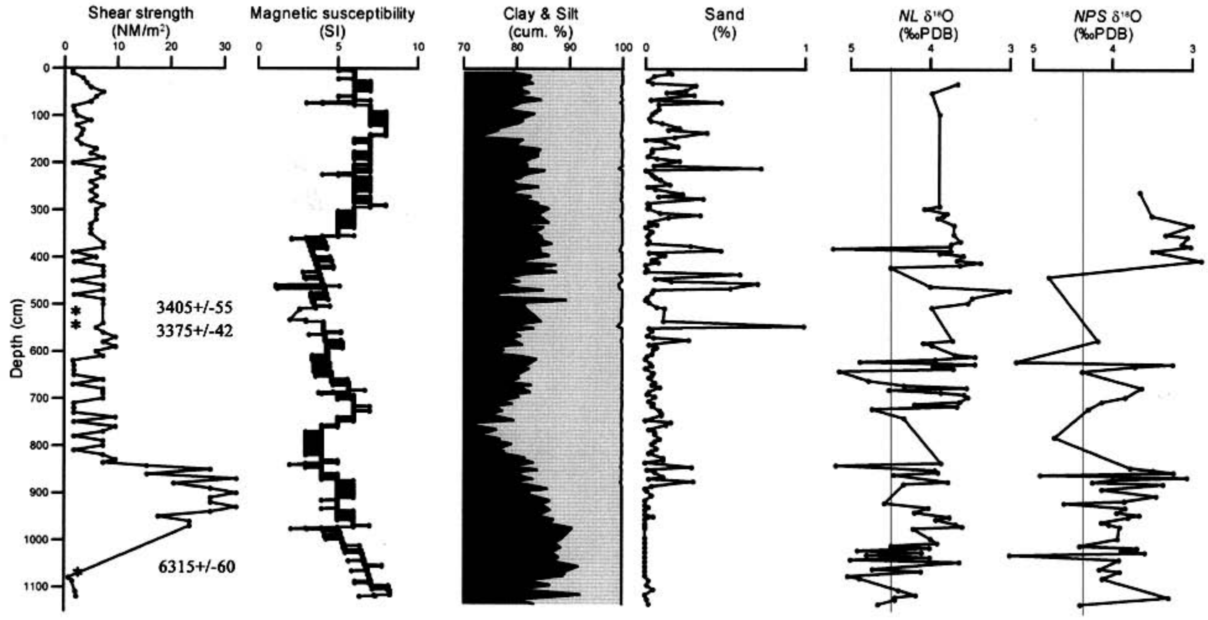

Fig. 5: Core LSSL2001-006P, Shear strength, magnetic susceptibility, grain size (cumulative clay - gray shading- and silt contents), sand content and oxygen isotope records of benthic (NL = *Nonionella labradoricum*) and planktonic foraminifera (NPS = *Neogloboquadrina pachyderma sinistral*). Asterisks locate radiocarbon ages from shells.

this region (Smith et al. 1994). The coarse sediment indicates greater influx of ice-rafted detritus (IRD) over the past 2000 years, and reworked Ordovician acritarchs above 25 cm core-depth indicate glacier calving from Devon Island and iceberg melting during the past ~100 years.

Benthic foraminifera and common small shells are present throughout Core 6 although planktonic foraminifera are rare in the top 200 cm. Benthic foraminiferal assemblages (Fig. 6) contain a diverse fauna with about 50 % agglutinated species, predominantly *Reophax arctica* and *Textularia torquata.* The abundance of individuals decreases upwards and *Stetsonia arctica* is more common below 7 m depth, together with the occurrence of *Fursenkoina fusiformis* and *Eggerella advena.* Planktonic foraminifera are virtually absent at the top of the core (Fig. 5). $\delta^{18}O$ isotopic records for both planktonic *(Neogloboquadrina pachyderma sinistral)* and benthic foraminifera *(Nonionella labradoricum)* show heavy values ranging from ~3-5 ‰, indicating that all these microbiota live in the cold, saline water layer below 125 m. Large-scale (~2 ‰) oscillations in $\delta^{18}O$ values occur at intervals of about 2000 years.

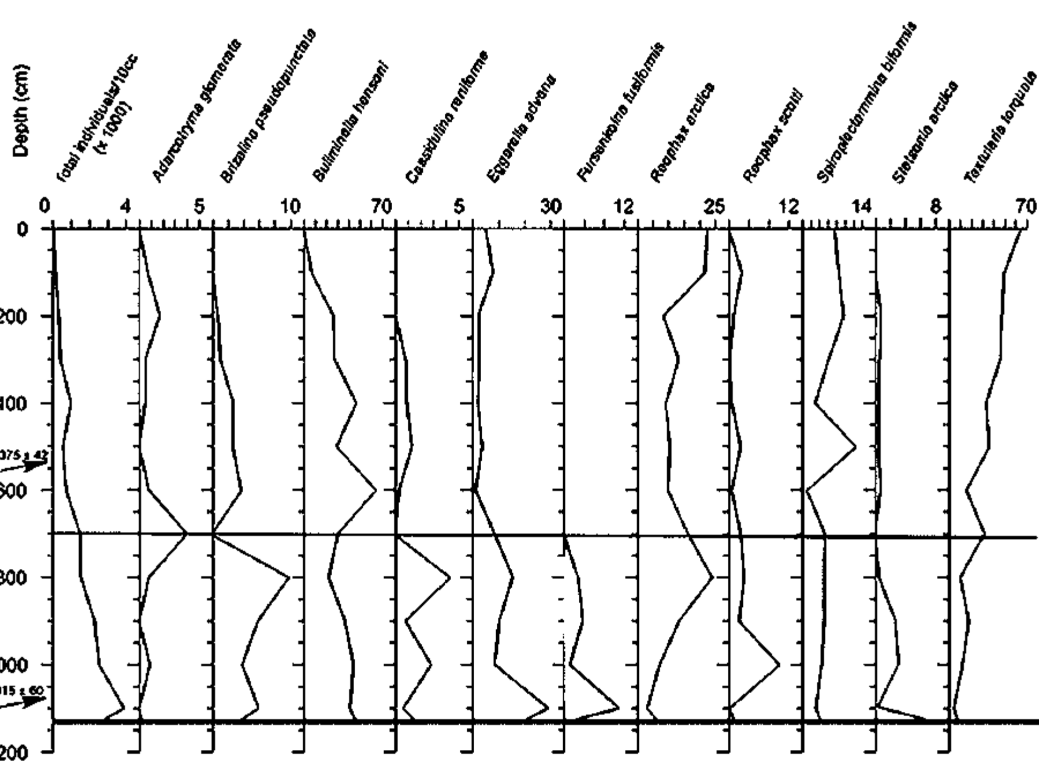

Fig. 6: Core LSSL2001-006P: Variations on total abundance of individuals and relative abundances of the most common species of benthic foraminifera.

Dinocysts dominate the palynomorph assemblages in Core 6 (Fig. 7) and their abundance also decreases upwards, with peak values occurring at about 1000 year intervals in the lower half of the core. Other palynomorphs are one to two orders of magnitude less abundant, but are consistently present, including Quaternary pollen and spores, linings of foraminiferal tests, the prasinophyte *Halodinium*, and reworked pre-Quaternary palynomorphs. Amorphous kerogen and fine-grained (rarely framboidal) pyrite is also abundant, together with smaller amounts of coaly and woody kerogen. Quarternary pollen-spore assemblages are dominated by dwarf (<25 μm) birch and tundra herb pollen, with variable amounts of pine *(Pinus)* and spruce *(Picea)* pollen indicating long distance wind transport. Reworked palynomorphs are mostly relatively unaltered bisaccates and triporate pollen grains, probably derived from the thick Tertiary sediments of the Axel Heiberg basin, but also including Cretaceous and Palaeozic spores. Paleozoic acritarchs are rare or absent except in the trigger weight core. The abundance of foraminiferal linings increases below 4.5 ka BP that is consistent with the increase in benthic foraminifera (Fig. 6). Phycomata of *Halodinium minor* and *H. major* (BUJAK 1984) show four abundance peaks at intervals of about 1000 years.

Dinocysts in Core 6 (ROCHON et al. 2003, in press) are dominated throughout by *Brigantedinium* spp. as also found in the North Water Polynya (LEVAC et al. 2001). Before about 4 ka BP, the co-dominant species are the Atlantic water indicators (MUDIE & SHORT 1985; AKSU & MUDIE 1986) *Operculodinium centrocarpum and Spiniferites elongatus* (including *S. frigidus and intergrades),* and temperate species such as *Pentapharsodinium dalei* and *Selenopemphix quanta* are present. After this time, the Arctic indicator, *Islandinium minutum* is co-dominant and the Arctic morphotype of *Polykrikos* (KUNZ-PIRRUNG 2001) increases. The palaeoceanographic reconstructions from the dinocyst assemblages (Fig. 8) show that although there has

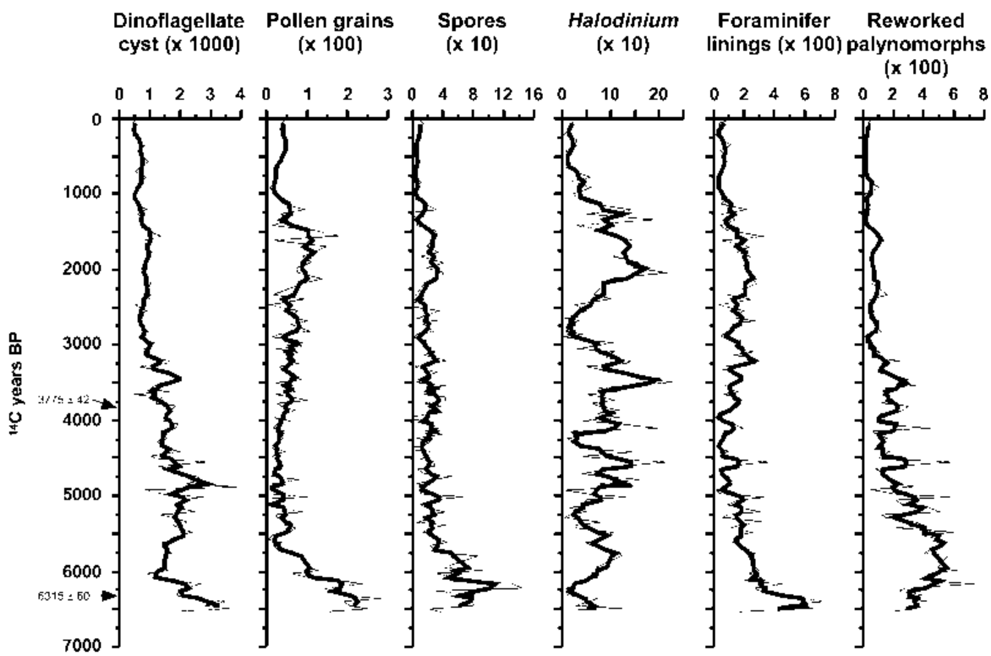

Fig. 7: Core LSSL2001-006 TWC&P, Quaternary palynomorph influx cm^{-2} yr^{-1}; numbers of dinoflagellate cysts; pollen grains; spores grains; prasinophytes (*Halodinium* spp.); foraminiferal linings; total reworked prequaternary palynomorphs (mostly bisaccate and triporate pollen; rare dinocysts and acritarchs). Bold black lines are running mean values.

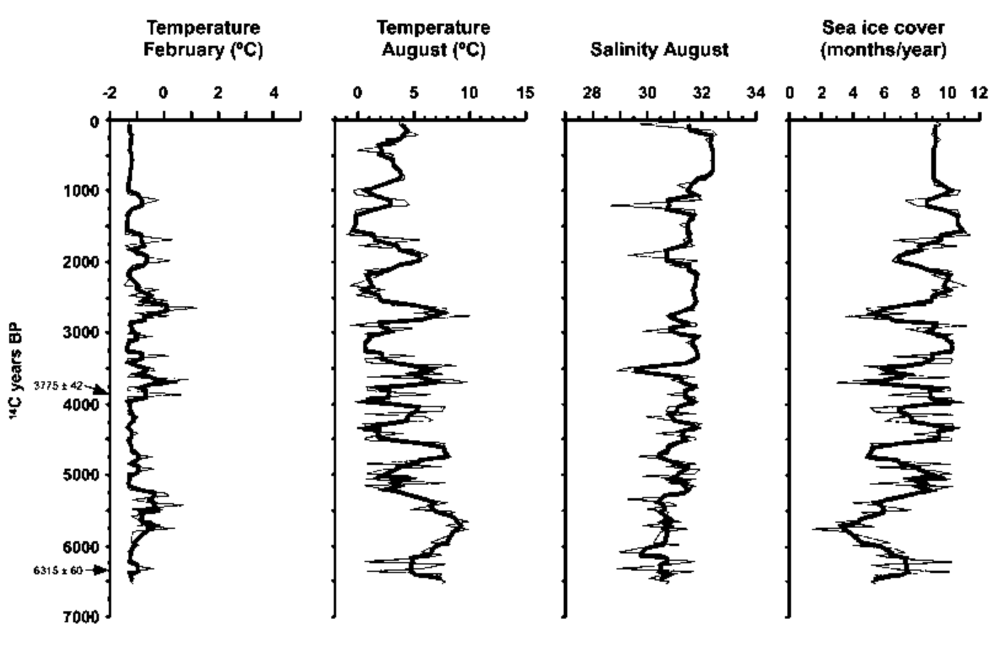

Fig. 8: Core LSSL2001-006 TWC&P; Quantitative paleoceanographic reconstructions of sea-surface temperature in winter and summer, surface salinity and duration of sea-ice cover >50 %, as determined from dinocyst assemblage data. Bold lines are median values, gray lines are maximum ranges.

been little change in winter temperature during the past ~6500 years, there have been large oscillations in summer SST from about 3 °C cooler than now to 6 °C warmer. These variations coincide with changes in sea-ice cover (SIC), from an additional two months of heavy (>50 %) SIC to a four-month extension of open water conditions compared to now. There are also many rapid fluctuations in salinity but these do not always coincide with the SST peaks and troughs. Overall, however, there is a gradual increase in salinity from ~30 to 32 psu and a corresponding decrease in mean August SST from about 7-4 °C.

Hall Basin

In Hall Basin, the site of LSSL2001-079 (Core 79) is located about 20 km beyond the Petermann Glacier at the southwestern end of Hall Basin (Fig. 1). Petermann Glacier is the longest outlet glacier (85 km) of the Greenland Ice sheet, with a 68 km-long floating ice shelf extending into Hall Basin beyond the fjord entrance. Huntec profiles in eastern Hall Basin (Fig. 2b) show that ~10 m of mud overlie a very thick (>40 m) stratified unit. Here SST is -1.4 °C (Fig. 3), the top of the thermocline is shallow (50 m depth), and the bottom water below 200 m is warmer (-0.4 to 0 °C) than in southern Nares Strait (E.P. Jones pers. comm. 2003). Surface salinity at the core site is not known, but is <31.4 psu above 50 m water depth in Kennedy Channel. The average SIC in Hall Basin presently is eleven months but is locally variable and there is often more open water on the east side where the ice usually drifts south.

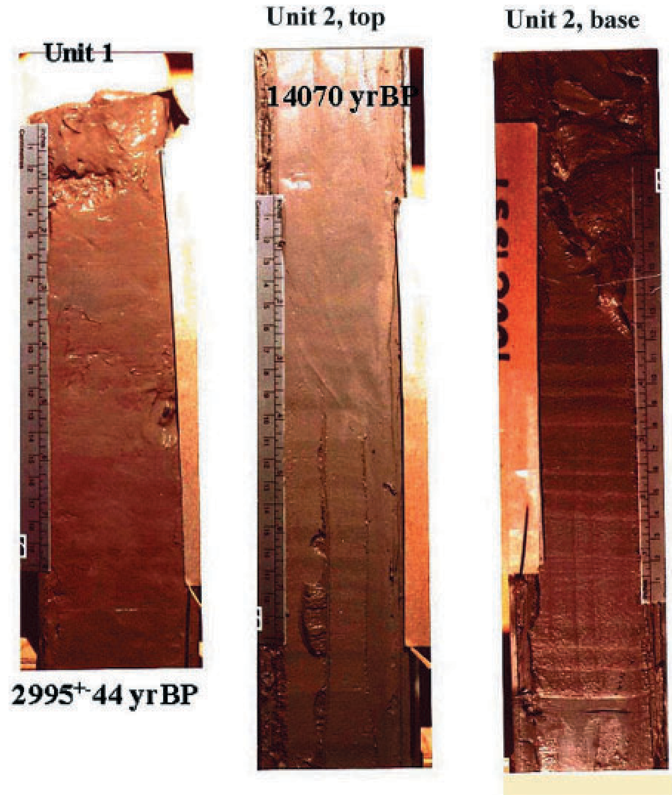

Fig. 9: Photographs of Core LSSL2001-079 showing lithofacies and radiocarbon ages; bioturbated (mottled) Unit 1 (0-20 cm), transition to Unit 2 at 400 cm (top of scale) and well-defined light-dark laminae in the lower part of Unit 2 (660-685 cm).

Core 79 (Fig. 9) contains ~8 m of clayey calcareous mud, with an upper 3.2 m long unit of faintly laminated brown mud (Unit 1) overlying ~5 m of brown and gray banded and laminated mud (Unit 2). The upper unit has diverse benthic and planktonic foraminifera, ostracodes and pteropods. Very small, delicate bivalves *(Lyonsiella abyssicola)* occur in the brown mud but they are too small and thin-walled for radiocarbon dating. AMS ages were therefore obtained from hand-picked foraminifera and show that Unit 1 has a maximum age of either 8.48 or 12.91 ka BP (see discussion). The banded mud has an AMS age of 14070 ±100 years BP at the top. The shear strength of the sediments is mostly less than 8 KN m^{-2} (Fig. 8) but increases below 5 m to about 15 KN m^{-2}. Below 2 m down core, the magnetic susceptibility is 2-3 times higher than in Core 6 although the sand content is lower. Inspection of all the grain-size distributions suggests that the grain-size variations are mainly related to changes in mixing between sediment with modal grain sizes of ~2 and ~20 μm, respectively. These variations in mixing are reflected by the abundance of the >9.3 μm sediment fraction (Fig. 10). As in southern Nares Strait, there is less than 1% of coarse sediment, but the amount of sand increases upwards.

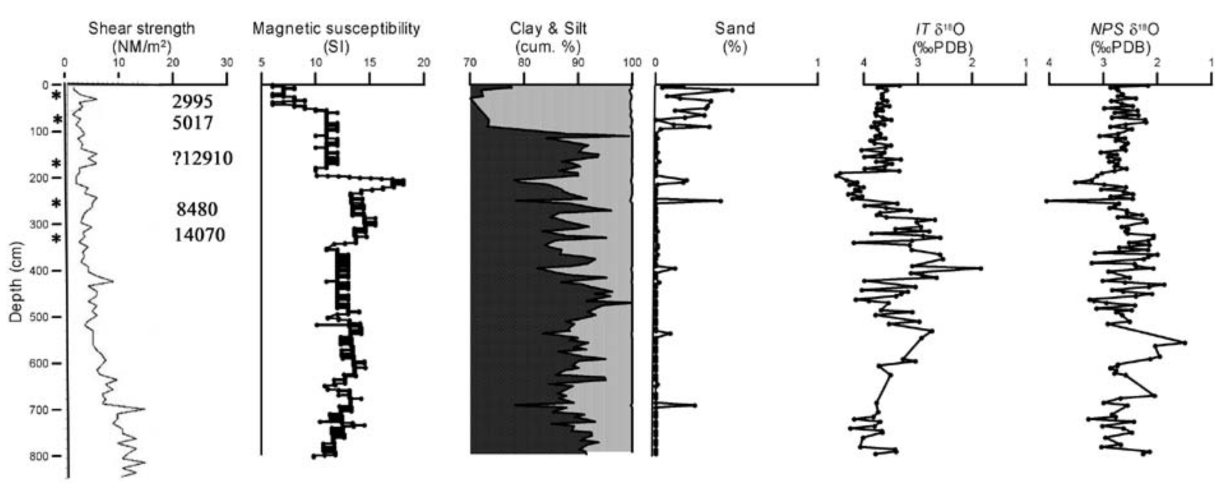

Fig. 10: Core LSSL2001-079: Shear strength, magnetic susceptibility, grain size (cumulative clay and silt contents, and sand content) and oxygen isotope records of benthic (IT = *Islandiella teretis*) and planktonic foraminifera (NPS = *Neogloboquadrina pachyderma* sinistral). Aterisks indicate corrected radiocarbon ages from foraminifera.

The $\delta^{18}O$ records for both planktonic *(Neogloboquadrina pachyderma* sinistral) and benthic foraminifera *(Islandiella teretis)* are consistently lighter (3-4 ‰) than in Core 6, presumably reflecting the presence of warmer water below 50 m. The $\delta^{18}O$ signal is also less variable throughout the core, suggesting smaller climatic oscillations on the polar margin. The abundance of benthic foraminifera (Fig. 11) is the same or less than in Core 6 except at the top where numbers rise to 16000 tests 10 cm^{-3}. The fauna is dominated by calcareous species, *Buliminella hensonii, Elphidium clavatum* and *Islandiella teretis,* but the agglutinant species *Spiroplectammina biformis* and *Textularia earlandii* are also present throughout. The banded sediment has common planktonics but lower numbers of benthic foraminifera, with assemblages dominated by the low salinity glaciomarine species *Elphidium clavatum.*

The palynomorph assemblages from Core 79 (Fig. 12) contain an order of magnitude lower abundances of dinoflagellate cysts and Quaternary sporomorphs compared to Core 6, and prasinophytes are virtually absent except for *Sigmopollis* spp. that are present throughout. On the other hand, foraminiferal linings are more abundant, particularly in the upper brown mud. About the same concentrations of reworked pre-Quaternary palynomorphs were found and increase towards the base of the core, where the occurrence of reworked bisaccate and angiosperm pollen decreases and the relative abundance of pre-Quaternary trilete spores increases. Overall, however, the pre-Quaternary assemblages comprise about ~90 % sporomorphs and 10 % dinocysts + acritarchs. Grey-brown amorphous organic matter (AOM) and coaly kerogen dominate the refractive particulate organic matter in the trigger weight core (Fig. 12b) where fluctuations of AOM correspond to changes in the $\delta^{18}O$ values. AOM is also abundant in Unit 1 of the piston core, but it decreases notably in the banded sediment unit, presumably reflecting the lower productivity of the pack ice-covered water.

Dinocyst assemblages in Core 79 are very low in diversity (N = 2-8 taxa) and are dominated (>50 %) throughout by *Brigantedinium* spp. and *Islandinium minutum.* Above 3 m, *Operculodinium centrocarpum* var. *arctica* is usually present and there are sporadic occurrences of *Spiniferites elongatus* and *Impagidinium pallidum.* In the lower half of the core, *Brigantedinium* spp. and *Islandinium minutum* are the only dinocyst species present. The abrupt decrease in dinocyst abundance at 3 m depth is comparable with that found at 8480 ±110 years BP in a core from southeastern Smith Sound (Levac et al. 2001) but the numbers of cysts present (10-20 per 1000 exotic spores) are too low to permit statistical analysis of these polar margin assemblages. Quaternary pollen-spore assemblages are dominated by dwarf (<25 μm) birch and tundra herb pollen, with common moss spores, including *Sphagnum* and *Polytrichum*-type spores. Wind transported bisaccate pollen are rare but fragments of moss leaves are common and usually associated with peaks of moss spores. *Sphagnum* spores and leaf fragments are the only Quaternary terrigenous palynomorphs present in the banded sediment unit.

Richardson Fiord and Mackinson Inlet

Richardson Fiord, at the inner end of Richardson Bay, and Mackinson Inlet are large branched valleys on the east coast of Ellesmere Island that are fed by glaciers from the Agassiz and Prince of Wales icecaps, respectively. Richardson Fiord enters John Richardson Bay on the northwest side of Kane Basin. This entire bay is narrow and steep-sided, and has two large glaciers at the inner end. Huntec records show that only the outer basin contains thick Holocene muds. Core LSSL2001-039 (Core 39) was recovered from189 m water depth at 80°06' N, 70°40' W and consists of ~2 m of dark gray bioturbated clayey mud with numerous dropstones overlying ~2 m of laminated gray mud with common foraminifera, and a sandy / gravelly diamicton at the base. The surface unit appears to be correlative with the Holocene section in Coburg Polynya while the laminated mud is probably an early Holocene distal glacio-

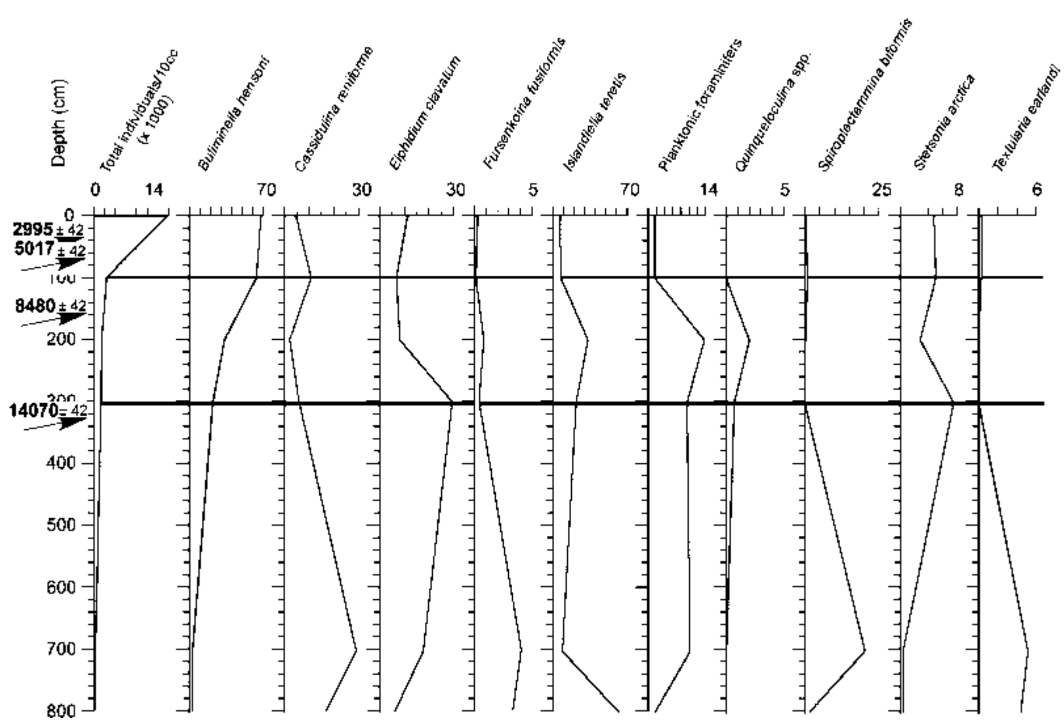

Fig. 11: Core LSSL2001-079P: Benthic foraminifera, variations in total abundance of individuals and relative abundances of most common species. Horizotal lines correspond to major changes in foram abundance and to lithofacies changes described as in the text.

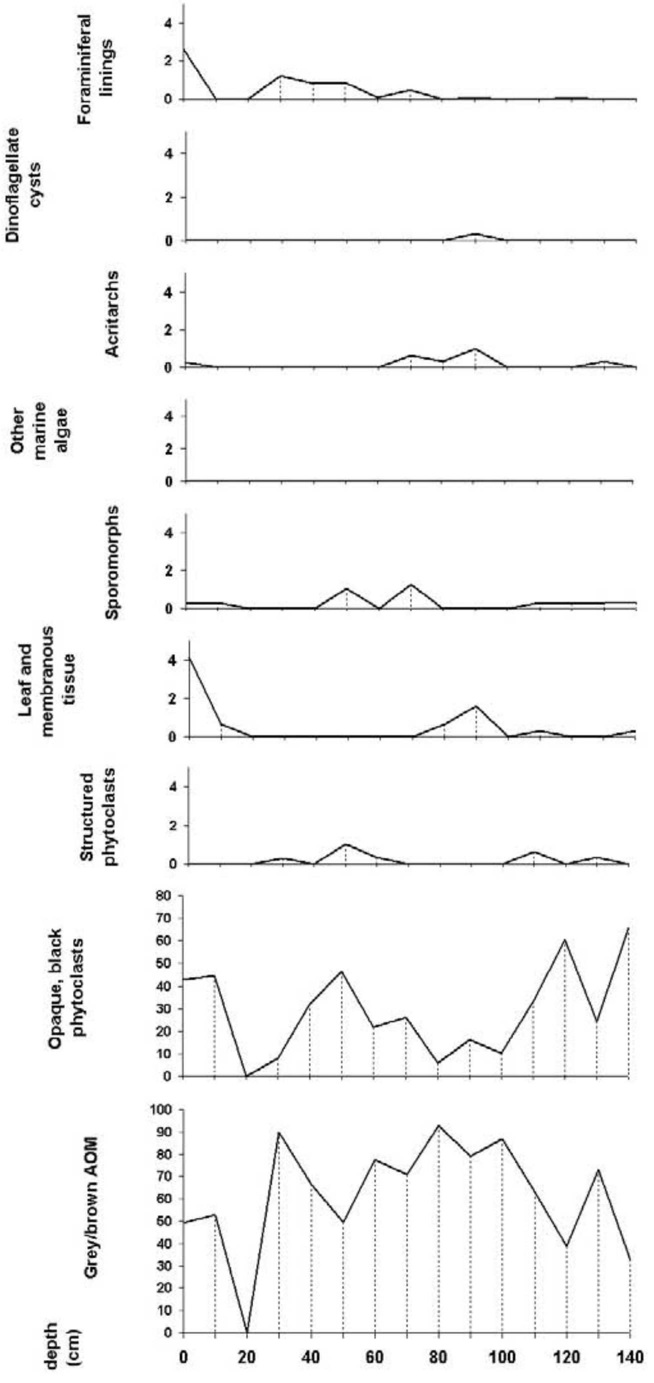

Fig. 12a: Palynomorph assemblages from Core LSSL2001-079P. Trigger weight core: relative abundances as percentage of total palynomorphs; coal = coaly kerogen; AOM = amorphous organic matter.

marine unit similar to that found in Hudson Strait cores (MacLean et al. 1992). A *Portlandia arctica* shell age of 8050 ±90 years BP has been reported for glaciomarine silt above till on the shore near Core 39 (England 1999). An earlier age of 13 ka BP or shell in Radmore Harbour immediately north of John Richardson Bay is considered unreliable (England 1999).

Mackinson Inlet joins northwest Smith Sound at about 77° 59.95' N, 79°39.75' W. The entrance to this fiord is frequently blocked by ice pouring out of Smith Sound, and this limited coring to a large box core (LSSL2001-131) at a water depth of 245 m in the outer channel. The corer recovered 52 cm of soft

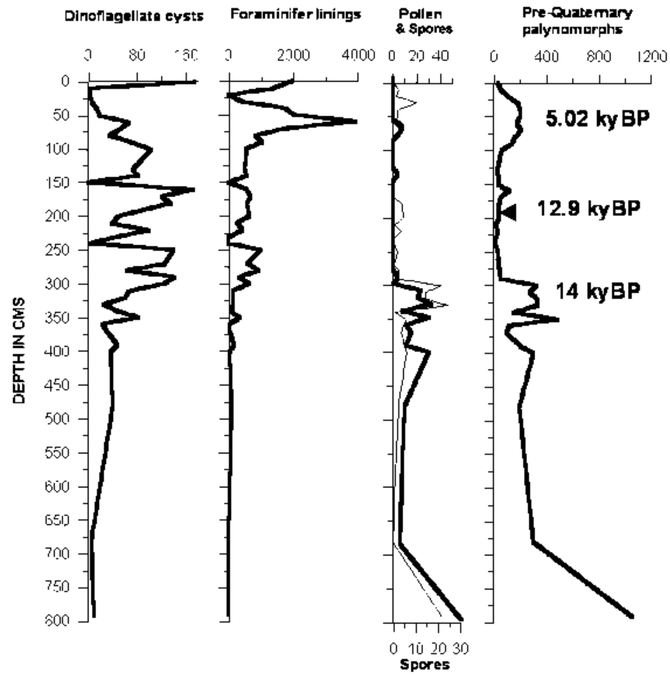

Fig. 12b: Palynomorph assemblages from Core LSSL2001-0079P; piston core palynomorph abundances per cm^3, with bold lines delineating the decrease in total foraminifera at ~75 cm in Unit 1, and the boundary between Units 1 and 2.

sulfide-rich highly bioturbated mud with a few small drop-stones, abundant small worm tubes (~0.5-1 cm long), and rare large sea cucumbers ~10 cm long and 1-2 cm thick. The heavy bioturbation at this site reduces its suitability for high-resolution palaeoceanographic studies but a longer core would be useful for further investigation of the history of Ellesmere Island ice dynamics. The youngest shell ages of 19, 22 and 22.5 ka BP from tills in Flagler Bay just north of Smith Strait are believed to mark the advance of Late Wisconsinan ice into Kane Basin and beginning the blockage of northern Nares Strait until 7.5-8 ka BP (England et al. 2000). However, inner Makinson Fjord was deglaciated by 9 ka BP (Blake 1977), suggesting that the ice adjacent to Smith Sound retreated earlier than in Kane Basin.

DISCUSSION

Lithofacies interpretation, distribution and regional correlation.

Previous geomarine studies in the southern Nares Strait region (MacLean et al. 1984, Kravitz 1982, Blake et al. 1996) and in other major channels of the CAA (Maclean et al. 1992, Andrews et al. 1991) have shown that the postglacial sediment cover is thin on the shelves and channels above ~100 m in most areas, probably because of strong currents and cold surface temperatures restricting meltout of berg ice. In eastern Baffin Island, much of the sediment from retreating glaciers is also trapped in over-deepened nearshore fjord basins (see Syvitski & Shaw 1995), and strong currents prevent the deposition of fine-grained sediment except in shelf basins below about 200 m water depth (Praeg et al. 1986).

In Nares Strait, most of Kane Basin contains a thin (<0.5 m) cover of soft, silty clay with gravelly IRD that overlies stiff sandy gravelly glacial till (Andrews et al.1991). In Lancaster Sound, the gravelly glacial diamicton has a shear strength of >20 KN m^{-2} and is overlain by stiff, acoustically stratified sediment (laminated sandy and gravelly glaciomarine mud) with an age of >8 ka BP. On Cruise LSSL2001, grab sampling at 200 m on the Northumberland shelf north of Thule recovered only sandy mud with abundant IRD gravel and pebbles, the main lithology being Thule Supergroup yellow sandstone and Precambrian gneisses. Here the benthos includeed brittle stars, small starfish and common bivalves (mostly *Macoma nasuta*). At 80°08.17' N, 70°13.5' W on the west side of Smith Sound, black fine sandstones and carbonates are the dominant IRD lithologies. The benthos contained one very large "basket" feather star, a few small sea urchins and brittle stars, rare small bivalves, and one live barnacle attached to a cobblestone. In Kennedy Channel, at 410 m, about 50 cm of gravelly, sandy calcareous mud were recovered above a thin layer of diamicton with pebbles and FeMn-stained slate. The diamicton contained very large, chalky foraminifera of probable Tertiary age.

In Jones Sound, the fine-grained sediment with mid to late Holocene shell ages in Core 6 clearly represents rapid (16-19 cm/100 y) postglacial deposition since about 7000 years BP. Some of these features are typical of the North Water (NOW) Arctic polynya environment (e.g., Levac et al. 2001) where 9 m of soft olive gray mud with an age of 6.8 ka BP (uncorrected) at 8 m was recovered from 663 m water depth. The bioturbated soft sediment with a diverse benthic foraminiferal fauna in Core 6 also resembles that found in seismo-stratigraphic Unit 5 and Faunal Zone D from Hudson Strait (MacLean et al. 1992), and in Unit 1 in Lancaster Sound. These lithofacies also have basal ages of ~8000 years BP that mark the time of glacial ice retreat from the southern channels. This retreat coincides with that of the Jakobshaven Isfjord glacier, Disko Bugt, West Greenland, to a position inside the present day fjord system (Lloyd et al. 2005), and may be part of large-scale glacial ice retreat in the Baffin Bay region.

The near-absence of coarse sediment from Core 6 indicates that large sediment-laden icebergs from West Greenland have not melted out in Coburg Polynya in postglacial times, in contrast to the gravelly sandy sediment deposited on the Northumberland and Makinson shelves further north. About 30 % of the shoreline of northeast Devon Island is lined by tidewater glacier fronts 55-100 m high (Taylor & Frobel 1984), most of which are presently receding, although retreat of the largest Sverdrup Glacier has slowed down. Melting is the most important mechanism of retreat but some calving of the glacier front also occurs. These local icebergs carrying sediment from the Lower Paleozoic marine limestones of Devon Island are the most likely source of the sand in Core 6.

Most of the present shelf area above 500 m in Jones Sound is covered by sediment with a grain size >4 μm, including coarse-grained till or modified till. The basins contain hemipelagic muds comprising amorphous and particulate organic matter (mostly foraminifera, dinoflagellates and diatoms) deposited from the productive waters and clays deposited by ice-rafting and, during the early Holocene, clay-sized particles winnowed from the shelves (MacLean et al. 1984). There is a large submarine moraine about 2 km offshore at about 290 m water depth and sediment gravity flows across the ice-proximal fore-slope may have been an important agent in the transfer and deposition of the banded distal glaciomarine sediment in the proglacial basins (Taylor & Frobel 1984). Correlation of cores using seismostratigraphic data shows that the soft, bioturbated mud with an age of <7 ka in Core 6 overlies early Holocene stratified marine sediments and Late Pleistocene gravelly till. For example, in Core HU83-023-052 from the edge of Coburg Basin, shell ages are 8.6 ka BP for the stratified sediment and the till has shell ages of 19.6 and 20 ka (Williams 1986). This sediment sequence is consistent with the Taylor-Frobel model for sediment deposition in the deep basin south of Coburg Island.

At the 81°28.3' N in Hall Basin, at the northern end of Nares Strait, the AMS ages clearly indicate that sedimentation rates in Core 79 are much slower (7.6-30.4 cm/1000 y) than in southern Nares Strait. However, this sedimentation rate appears to be 2-4 times higher than the youngest sediments presently found under pack ice at about 81 °N, 94 °W on the Canadian polar shelf off Axel Heiberg Island (van Wagoner et al. 1989, Hein & Mudie 1991). Precise estimation of sedimentation rates in Core 79, however, is hampered by uncertainty about the overlap between piston and trigger weight cores and about the correctness of the AMS ages at depths of 181 cm (12910 ±70 years BP) and at 258 cm (8480 ±110 years BP). Initially, it appeared that the younger age was incorrect because the dated sample was very small (0.05 mg). However, the bioturbated mud and the composition and relatively high diversity of the foraminiferal assemblage from 258 cm in Core 79 are similar to those in Facies B and C on the Polar Margin that have ages of 9420 and 9570 years BP, respectively. This suggests that the AMS age of ~8.5 ka BP at 258 cm is correct and the older age of 12.9 ka BP age from an interval of unusually high foraminiferal tests (0.43 mg, two times higher than the average weight) is incorrect because of an interval of re-deposition from IRD or thin turbidity currents. Overall, however, the uniformity of assemblage composition in Unit 2 and the persistent presence of Arctic deep water species (Scott & Vilks 1991) that cannot be transported up-slope shows that the benthic forams in Core 79 are largely in place and not transported from the shelf as found at shallower sites on the northwestern European margin (Heier-Nelsen et al. 1995). The apparently slow average sedimentation rate for the interval from 322 to 258 cm is also similar to that occuring beneath the perennial sea-ice on the Axel Heiberg margin (Hein & Mudie 1991). This perennial or pack ice is any drift ice with more than 7/10 cover, and it includes all multiyear floating ice but it does not include fast-ice that is grounded or attached to the land. This multiyear ice does not melt-out in the summer but it may be broken-up by extensive leads.

The top (0-1m) of the bioturbated fine-grained brown mud in Core 79 PC (Unit 1) has abundant foraminifera, diatoms, ostracodes, silt and some sand (IRD) as found in the youngest Facies A on the polar shelf. It is notable, however, that the Polar Margin Facies A contains common IRD pebbles and sand, and a much higher diversity (48-53 spp) of arenaceous benthic foraminifera than in Hall Basin where there are 15-20 spp. Facies A has an age of 7.15 ka BP; the uppermost heavily bioturbated brown mud unit in Core 79 has an age of 5107 ±47 years BP at 83 cm just above its base at 100 cm where discontinuous wispy laminate appear and foraminiferal abundance decrease by more than one order of magnitude (Fig.11). The absence of gravel and pebbles suggests that there is either less melt-out of sediment-laden IRD in Hall Basin where the sea-ice usually moves southwards in summer than on the Polar Shelf, or that most of the coarse sediment from the Petermann Glacier is deposited in the fjord and on the adjacent continental shelf. The latter possibility seems supported by observations that the escape of calf-ice from the Petermann Glacier is restricted because of damming back by ice in other fjords of the area (Kelly & Bennike 1992). The increase in silt and slight increase in sand content from ~80-30 cm core depth coincides with the retreat of the glacier from ~7.5-4 ka BP. The slight decrease in silt and sand at the top may reflect the subsequent advance of the Petermann Glacier during the Little Ice Age that only ended in 1922, after which the floating glacier tongue retreated ~6 km by 1992 (Kelly & Bennike 1992).

The banded and laminated sediment (Unit 2) in Core 79 has a gradual boundary at the top (around 400 cm; Fig. 9B) beneath the brown clay of Unit 2 with an age of 14070 ±100 years BP at 322 cm. Below about 650 cm, most of the parallel-laminated sediment have upgraded alternating gray and brown laminae with sharp contacts. Most of the couplets are 1-2 cm thick, with thin (few mm) light brown laminae alternating with thicker gray laminate. Some of the gray laminae contain closely spaced, millimeter-scale faint brown and gray laminae. The upper part of the banded unit has less well-defined lamination without sharp contacts, suggesting some bioturbational mixing within and between the couplets.

Unit 2 in Core 79 is similar to parts of Facies D on the Canadian polar shelf (Hein & Mudie 1991) where a variably laminated sandy-silty mud with low numbers of benthic and planktonic foraminifera has an age of 9950 years BP at the top. Facies D is estimated to have a relatively high sedimentation rate of 134 cm/1000 y and has been interpreted as a fine-grained turbidite facies deposited in relatively open water conditions during the retreat of glacial ice from the north coast of the CAA, about 10 ka. The finer-grained texture, absence of sand and lack of visible grading in Unit 2 of Core 79 suggests that this banded unit is not a turbidite but represents suspension sediments supplied by melt water plumes beneath a semi-permanent pack ice cover. Laminated sediment representing proximal glaciomarine environments in the shallower southern channels (MacLean et al. 1984) differ in that planktonic foraminifera are absent and the benthic fauna is dominated (~90 % or more) by *Elphidium clavatum* and *Cassidulina reniformis.* Although more work is required to determine the exact nature of banded deposit in Core 79, the lithological and geotechnical properties clearly show that it represents sediment deposition under floating sea-ice, despite an age of more than ~14 ka BP for its top. The presence of the Arctic deep-water species *Stetsonia arctica* and the diversity of the assemblages exclude the interpretation of a distal glaciomarine environment. Smear slides also suggest that the alternating brown and gray laminae have more or less carbonate and quartz silt, respectively, but more detailed petrologic studies are required to determine if these represent seasonal changes within annual varves or longer-term pulsating events, such as wetter-drier climate cycles and variations in bottom currents.

Benthic foraminifera and palaeoproduction

In Core 6, there is some interesting variation of benthic assemblages down-core (Fig. 6). The presence of common agglutinated species throughout the past ~6.5 ka BP may suggest either highly productive summer-open polynya conditions or the presence of the cold Baffin Current as found off southeastern Canada after 4 ka (Scott et al. 1984, 1989c). High productivity would be consistent with the continuous presence of high phytoplankton abundances, including the dinocysts (Fig. 7) and large (>63 μm) centric and needle-shaped pennate diatoms. High diatom abundance was also reported for the Holocene section of the neighboring Core HU83-023-052 (Williams 1990). Diatom studies of cores from Disko Bugt (Jensen et al. 2003) likewise indicate that a warm interval occurred from 4.8-4.0 ka BP in eastern Baffin Bay, during which time productivity was high and stratification increased.

What is most interesting, however, is the occurrence of *Buliminella hensoni* before 3375 years BP and *Stetsonia arctica* before ~6 ka. These species are typically deep water Arctic species (Scott & Vilks 1991) and suggest penetration of deep Arctic water to this site until relatively recently. It is notable that these two species disappear in Jones Sound at about the same time that southeastern Canada experiences a cooling (Scott & Collins *1996). The higher percentages of Stetsonia arctica* below those of *B. hensoni* may indicate a difference in bottom water input from the deep Arctic before ~6 ka. The presence of *Fursenkoina fusiformis* below 7 m depth in Core 6 may indicate that the bottom water was less well oxygenated before ~4 ka BP; the lower oxygen could reflect either higher productivity or more sea ice that would have slowed bottom water circulation, as suggested for areas further south during the glacial maximum (Scott et al. 1989). The latter interpretation for the bottom water conditions, however, conflicts with the dinocyst evidence for warmer surface water until 4 ka BP (Fig. 8). An increase in the magnitude of the vertical temperature gradient would result in stronger stratification and reduced oxygenation of the bottom water. Higher dinocyst abundance and the presence of *F. fusiformis* from ~7 to 4 ka BP could also indicate greater production of organic matter.

High-resolution studies have not yet been made of the benthic foraminifera in Core 79, but the initial results (Fig. 11) clearly show that despite the late glacial age, the sediment in Unit 2 was not deposited by grounded ice. In fact, the species present, with high percentages of *Buliminella hensoni* and *Islandiella teretis* and some *Stetsonia arctica,* are much more suggestive of slope to deep Arctic Ocean conditions than proximal glaciomarine faunas such as the *Elphidium-Cassidulina* fauna normally found in proximal glaciomarine conditions (MacLean et al. 1992, Osterman & Andrews 1983). The presence of *F. fusiformis* in the banded sediment may again indicate that the bottom waters were less well oxygenated during the Late Glacial than during the Holocene, possibly because of a continuous pack ice cover that would reduce atmospheric exchange of gases and restrict vertical mixing. Lack of drift-wood on raised beaches in North Greenland also indicates the presence of perennial fast ice in the early Holocene, but no driftwood data are available for the northern end of Nares Strait (Dyke et al. 1997)

Stable isotopes and planktonic foraminifera

The $\delta^{18}O$ values for both planktonic and benthic foraminifera in Core 6 are remarkably heavy: ~2-5 ‰ for *N. pachyderma* and ~3.5-5.5 ‰ for *N. labradorica* in contrast to values of ~2-3.5 and 4-5 ‰ for N. *pachyderma* and *Oridarsalis umbonatus* from the central Arctic Ocean (Scott et al. 1989). It appears that in Jones Sound, *N. pachyderma* lives primarily in the cold-water layer below 125 m, perhaps avoiding the large salinity fluctuations in the surface layer caused by down-welling of glacial melt water 0.5-5 km from the ice front (Horne 1989). There are decreases of about 1 ‰ from the base towards the tops of the records for both planktonic and benthic species, but there are insufficient *N. pachyderma* above 225 cm for a complete record. There is also a slight indication of large-scale (~1-2 ‰) shifts in $\delta^{18}O$ values of *N. pachyderma* at intervals of about 2000 years, which is the length of most cycles of cultural change in the archaeological records (Savelle & Dyke 2002 and refs therein).

The $\delta^{18}O$ records for both benthic and planktonic foraminifera in Core 79 are consistently lighter (3-4 ‰) than in Jones Sound, apparently reflecting the persistence of warmer water below 50 m. The $\delta^{18}O$ signal is also less variable than in the south, suggesting smaller climatic oscillations on the polar margin. The signals of both *N. pachyderma* and *I. teretis* show about 0.5 ‰ heavier values below 5 m, perhaps reflecting colder, more saline conditions during the Late Glacial interval, and increased melt water during the Holocene.

Dinoflagellate cysts and past changes in SST, salinity and sea ice extent

The paleoceanographic reconstructions from the dinocyst assemblages (Fig. 8) show that although there has been little change in winter temperature over the past ~6500 years, there have been large oscillations in summer SST that coincide with changes in SIC. There are also many rapid fluctuations in salinity but these do not always match the SST peaks and troughs. Overall, however, there is a gradual increase in salinity from ~30 to 32 psu and a corresponding decrease in mean August SST from about 7 to 4 °C.

The SST reconstructions for Core 6 indicate that from ~6500 to 3300 years BP, there were large oscillations in summer SST from 3 °C cooler than now to 6 °C warmer, and these temperature changes correspond to variations in SIC ranging from two months more of heavy (>50 %) ice to a four-month extension of open water conditions compared to now. These temperature and SIC changes appear to begin and end within about 50 to 100 years and to re-occur at intervals of ~1000 years. This periodicity is close to the 1100-1500-year Bond Cycle. The oscillations in Core 6 probably correspond to the same forcing factor although the resolution of the response signals may be modified by the bioturbational mixing depth of about 15 cm (equal to 79-94 years), based on measured rates in Bylot Sound off eastern Smith Sound (Smith et al. 1994).

Nonetheless, the palaeoceanographic reconstructions show that the GCM predictions of +4 °C for continued global warming are represented in southern Nares Strait for several intervals during the mid-Holocene when solar insolation and ice sheet sizes were essentially the same as now. The most recent of these warming events, about ~2700 years ago, in southern Nares Strait shows that sea ice cover could be as low as two months per year. If this is correct, then access to Grise Fiord and hence, into the Sverdrup Basin, could be accomplished essentially year-round by ships other than large ice-breakers. However, our records also show that these warmer intervals only last a few 100 years and are replaced by extended intervals with one to two months of almost continuous SIC. These climate oscillations are more rapid than those in the archaeological record of changing human populations in the Canadian Arctic and northern Greenland.

Time and extent of the Late Glacial Maximum (LGM) ice margins

The presence of glacial erratic boulders (granites and gneisses) of Greenland origin at 840 m above sea level on Ellesmere Island northwest of Kane Basin and absence of mollusks with ages of ~13 to 19 Ka in raised marine deposits along Nares Strait has led to the suggestion that ice from Greenland and from an extensive Innuitian ice sheet filled most of Nares Strait until about 10 ka (England 1999, England et al. 2000, Dyke 2000). This hypothesis is further supported by Cl-36 ages from Hans Island in central Kennedy Channel (Zreda et al. 1999) that seem to indicate glacial ice over Kennedy Channel until at least 10 ka BP.

Dyke (2000) also reports geomorphologic evidence for an extensive Innuitian ice sheet and a late (~10 ka) retreat of the Devon Icecap. Our data from cores 6 and 52 in Jones Sound support that model. In contrast, our data from Hall Basin clearly show that there has been no grounded ice off north-western Greenland during the past 14000 years. Therefore, although it is possible that the Greenland Ice sheet filled the relatively shallow (~200 m) Kane Basin and may have extended northward through the 400 m-deep Kennedy Channel to Hans Island during the glacial maximum 18-22 ka, it did not fill the deeper basin to the north during the Late Wisconsinan (Weichselian). The absence of Greenland ice filling the Hall Basin during the latest Pleistocene may explain the anomalously slow emergence curve for Hall Land, where the marine limit is dated as ~9.5-10 ka (Kelly & Bennike 1992). Furthermore, an age of >20 ka for the Kap Fulford Stade would mean that the Nyboe Land marine transgression was related to the isostatic depression associated with the Warming Land Stade from ~9.5-8 ka, rather than the earlier Kap Fulford Stade. It is also clear that off Hall Land, the Greenland ice did not extend as far offshore during the Warming Land Stade as postulated by Kelley & Bennike (1992, Fig. 13). Retreat of a floating ice tongue from Hall Bay and Petermann Fiord by 8 ka, however, is consistent with an age of 8.6 ka for the base of Unit 1 in Core 79 and is consistent with the decrease in *Fursenkoina fusiformis* that would follow an increase in circulation after the break-up of the ice shelf.

Likewise, at the southern end of Nares Strait, AMS ages of 10.4 ka BP for benthic foraminifera in a core from near Carey Øer, west of Thule (Levac et al. 2001) also show that the grounded ice had retreated from eastern Smith Sound at 10.4 ka BP. This means that the hypothetical merging of Ellesmere and Greenland ice margins in southern Nares Strait at 10 ka (England 1999) is incorrect. An earlier retreat of Greenland ice from Nares Strait may also require re-evaluation of the thickness of this ice sheet, and hence, the dynamics of isostatic rebound in this region. Recent foraminiferal studies (Lloyd et al. 2004) of cores taken in Disko Bugt, West Greenland, demonstrate deglaciation of the main part of Disko Bugt at a minimum of ~10.2 ka BP, thus implying a relatively early glacial ice retreat in other parts of the Greenland ice sheet margin around Baffin Bay. A less extensive Greenland Ice sheet would also affect the age and dynamics of Innuitian Ice retreat from Ellesmere Island fjords such as Richardson and Makinson. Thus, as on the Canadian polar margin north of Axel Heiberg and in northern Ellesmere Island (Hein & Mudie 1991), palaeoceanographic data from the modern shelf and fjord basins provide crucially important reference points for evaluating models regarding the extent of the Ellesmere and Greenland ice sheets at the end of the last glaciation, and the timing of ice retreat from the margins of the Canadian Arctic Archipelago.

CONCLUSIONS

• Long piston cores of no over-compacted sediments from deep basins in Nares Strait have been dated by multiple mollusk and/or foraminiferal shell ages to provide continuous proxy-climatic records for the past ~8 to >14000 years in the eastern Canadian Arctic and Northwest Greenland.
• Shear strength measurements, visual sediment characteristics, detailed grain size and microfossil analyses indicate that contrary to previous geomorphologic models, there was no grounded ice in eastern Hall Basin during the Late Wisconsinan glaciation.
• Planktonic and benthic foraminiferal faunas and their stable isotope oxygen and carbon records in Core 6 show that highly productive summer-open polynya conditions have persisted off Coburg Island for the past 7 ka although the water column may have been more highly stratified and bottom water less well oxygenated before ~4 ka BP. The longer record for Core 79 in Hall Basin indicates that climatic oscillations on the polar margin have been smaller than in the south, probably with colder, more saline conditions (deep Arctic water) during the late glacial interval, and increased melt water during the Holocene.
• Benthic foraminiferal assemblages and persistent presence of planktonic foraminifera in Core 79 show that there has been no grounded ice off Petermann Glacier for the past 20000 years BP. Fluctuations in abundances of the foraminafera are probably related to changes in the duration and thickness of sea ice cover.
• Palaeoceanographic reconstructions from dinocysts in Core 6 indicate that from ~6500 to 3300 years BP, there were large oscillations in summer SST from 3 °C cooler than now to 6 °C warmer, and there were corresponding variations in SIC ranging from two months more of heavy (>50 %) ice to a four-month extension of open water conditions compared to now. These temperature and SIC changes begin and end within about 50-100 years and re-occur at intervals of ~1000 years which is close to the 1100-1500-year Bond Cycle. Dinocyst abundances in Hall Basin are too low to permit quantitative palaeoclimatic reconstructions for the polar margin.
• Results of sedimentological and microfossil studies of the first marine sediment core from Hall Basin show that although the Greenland Ice sheet may have filled the relatively shallow (~200 m) Kane Basin and may have extended northward through the 400 m-deep Kennedy Channel to Hans Island during the glacial maximum 22-18 ka, it did not fill the deeper basin to the north at this time. The absence of Greenland ice in Hall Basin during the Late Pleistocene implies a less extensive Greenland Ice sheet that would also affect the timing and dynamics of Innuitian Ice retreat from Ellesmere Island fjords such as Richardson Fiord and Makinson Inlet.

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